

ACTIVE PEDESTRIAN PROTECTION

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ABSTRACT

Vulnerable road users, especially pedestrians, are more susceptible to fatal and serious injury compared with vehicle occupants. Although the frequency of accidents involving pedestrians has reduced in recent years, there are still approximately 800 pedestrians killed and 7,000 seriously injured every year in Great Britain. Furthermore, in the late nineties, more than 6,000 pedestrians were fatally injured annually on EU roads, accounting for approximately 20% of all road fatalities.

The kinematics of pedestrian impacts has been well documented and test procedures have been adopted by EuroNCAP and changes made to EU regulation. Whilst this is aimed at driving improved pedestrian-friendly car design, further benefits could be achieved with the use of pre-crash sensing and active safety systems. Such systems require sensors capable of accurately and reliably detecting the presence of a pedestrian prior to a collision, and activating protective countermeasures effectively in order to reduce the pedestrian injury risk.

Accident data has been collected as part of a project developing a sensing system for cars capable of detecting and reacting to the presence of pedestrians. Systems that use radar, infra-red, laser, or ultrasound sensors to scan the 'target area' for obstacles, must be intrinsically safe, accurate and reliable, yet low cost in mass-production. A sensor array comprising both radar and infra-red devices has been developed as part of a project for the UK Foresight Vehicle programme. Other work has involved systems that have been developed to demonstrate the potential for using external airbags to provide a means of protecting pedestrians during a frontal impact.

This paper examines the pedestrian accident data, and the specification and application for pre-crash sensing. Systems for pedestrian detection and protection have been developed and the research in these areas is described.

INTRODUCTION

Although the frequency of accidents involving pedestrians has declined over recent years, during 2003 there were 774 pedestrians killed in Great Britain and over 7,159 pedestrians who sustained seriously injury (DfT, 2004). These pedestrian fatalities account for 22% of all road traffic accident fatalities in Great Britain (DfT, 2004). A similar situation exists in the EU, where in 1999, 32,552 road users were killed on EU roads, of which, 6,196 (19%) were pedestrians (OECD, 2001). These figures demonstrate, both in societal and financial terms, the need for improved protection directed at this group of vulnerable road users. This paper describes the requirements for advanced pedestrian protection, which includes a system which detects pedestrians in the vehicle's path, together with a concept protection system designed to minimise injuries to pedestrians involved in an impact with a car.

There are many types of pedestrian protection system that may be considered for vehicles. These include driver warning, brake assist, automatic braking and collision avoidance (primary safety) and external airbags, 'pop-up' bonnets, and advanced energy-absorbing materials (secondary safety). This paper describes some of the findings from work carried out in the UK to develop a detection system that could be combined with an appropriate protection system. The detection system was developed by the Advanced Protection of Vulnerable Road Users project (APVRU) with the aid of funding from the UK Department for Trade and Industry Foresight Vehicle Programme. This followed on from work commissioned by the UK Department for Transport investigating active adaptive secondary safety (AASS, www.rmd.dft.gov.uk), which showed that pedestrian protection in the form of airbags sited on the bumper and bonnet of a vehicle had the potential to reduce significantly injury potential in 40 km/h (25mile/h) and 48 km/h (30mile/h) impacts. For example, experimental tests conducted as part of the AASS study showed that the Head Injury Criteria (HIC) could be reduced by 93%, chest acceleration by 49%, pelvis acceleration by 12% and lateral knee acceleration by 71% (Holding *et al*, 2001).

If a pedestrian protection system is to confer maximum benefit, the sensor system and algorithms play a vital role in detecting appropriate targets and determining when the system should and should not activate. The system must activate if a collision is imminent in order to reduce the injury risk to the pedestrian. However, the system must not react inadvertently, and must not expose the pedestrian, or interacting road users, to an

increased risk of injury than would otherwise occur without the safety system. Furthermore, the sensors must be capable of distinguishing between pedestrians and inanimate objects, such as roadside furniture. Other issues exist regarding the resetting of any deployable system, the use of which must be fully justified in cost benefit terms.

PEDESTRIAN INJURIES

Pedestrian injuries resulting from impacts with cars frequently result from a primary impact to the lower or upper leg, and depending on the speed of the impact, a secondary impact (often causing head injury) on the upper bonnet, windscreen or windscreen surround. Furthermore, there may be a tertiary impact with the ground and also a risk that the pedestrian may be struck by other vehicles. The injury severity resulting from the primary impact may be reduced by using, for example, soft bumpers. Pop up bonnet or airbag systems have the potential to protect against the secondary impact and may also provide a means of retaining the pedestrian on the vehicle bonnet in lower velocity impacts. Research by TRL using external airbags sited on the bumper and bonnet demonstrated the potential for retaining the pedestrian on the vehicle bonnet at the impact speeds tested (Holding *et al* 2001).

The impact velocity is perhaps the most important factor in determining the injury severity of an accident involving a pedestrian. For example, of 543 pedestrians who sustained head injury, Otte (1999) found that the risk of brain injury at 30 km/h was less than 20%, whereas at 40 km/h this risk had risen to 40%. Furthermore, according to the European Transport Safety Council, at impact velocities in excess of 50km/h (31mile/h), the likelihood of pedestrian survival is less than 50%. If however, the impact velocity is 30km/h (19mile/h) or less, approximately 90% of those

struck may survive (Carlsson, 1996). Accident data was investigated because the impact velocity has implications for the number of impacts in which injury mitigation may be successfully conferred. Furthermore, the range of real-life impact velocities for which injuries may be reduced has implications for the time available for the system to detect and react to an imminent impact.

Data from the TRL Fatals database (a Dft funded database analysing fatal police accident files - www.rmd.dft.gov.uk) was used to gain information estimates of the impact speed. The results of this analysis indicated that 6.4% of fatalities occurred at 32km/h (20mile/h) or less, 41.5% at 48km/h (30mile/h) or less and 70.6% at less than 64km/h (40mile/h). Otte (1999) also noted a strong bias towards low velocities, with approximately 70% of pedestrian impacts occurring at impact velocities up to 40km/h (25mile/h). In higher velocity impacts, Otte (1999) estimated the risk of serious (AIS 2-4) injury to be 65%. He also found that the head was the most seriously injured body region, with 60% of pedestrians involved in car impacts suffering head injuries, and that higher impact velocities were correlated with more severe head injuries. Thus, this indicates that a significant proportion of pedestrians are killed at impact speeds for which an advanced protection system using airbags on the bumper and bonnet has been shown to provide substantial protection (Holding *et al*, 2001).

Figure 1 shows the distribution of pedestrian injuries by impact point from the UK Fatals database. Analysis of this source shows that the body region most frequently injured was the head, 50.8% of cases. Multiple injuries accounted for 29.1% of cases. The next most frequently injured body regions were the thorax, 5.0%, and legs, 3.7%.

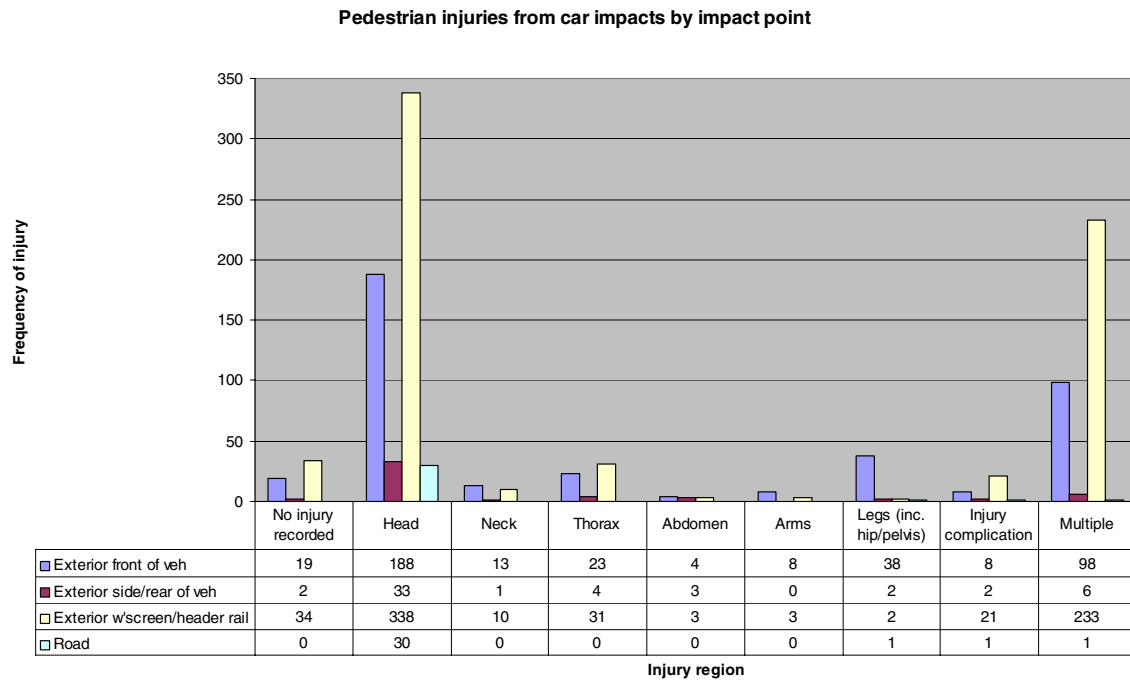


Figure 1. Frequency of pedestrian injuries by impact point (UK Fatals database)

Identification of the important injury mechanisms of pedestrian injury is essential for the development of an effective protective system. IHRA data, collected from a range of on-the-spot accident research projects, indicates that for injuries AIS \geq 2, the legs are the most frequently injured body region, 35.6%, followed by the head, 29.0%, chest, 12.5%, and neck, 10%. The discrepancy between this data and the UK Fatals database may be explained by the fact that in more severe accidents, the impact velocity is greater and the trajectory of the pedestrian is likely to result in a more severe head strike on the vehicle.

Stats19, the UK database on personal injury road accidents, resulting casualties, and the vehicles involved, data was also analysed for APVRU and showed that the majority of pedestrians hit by cars were crossing the road away from pedestrian crossings. This group accounted for 80.3% of the 1,203 pedestrian casualties. Over 25% of casualties were also recorded as not being seen by the driver of the impacting vehicle due to roadside obstructions to vision.

Holding *et al* (2001) has shown that protective airbags are successful at reducing injury potential in certain impacts up to 48km/h (30mile/h) when sited on the front of the vehicle to protect the legs from the initial contact, and also on the upper bonnet or lower windscreen frame to prevent head contact with the bonnet or windscreen area.

However, further research is required regarding the response of such a system in a wider range of accident configurations and impact speeds to ensure that the injury risk is not increased compared with non fitment.

SENSOR TECHNOLOGIES

It is apparent that accurate pre-crash sensing is critical to the successful application of advanced protection systems for vulnerable road users. Sensors need to be able to detect and track pedestrians over time and reliably distinguish the vulnerable road user from the environment. They also have a requirement to be unaffected by external influences for example: EMC, solar loading, wind, rain, fog and mud. The type of system chosen must respond sufficiently rapidly and accurately to permit the system to activate correctly to minimise the injuries sustained, hence the range and update rate of the sensors are important.

Research conducted as part of the APVRU project concluded that no single sensor will offer an acceptable solution, and that the problem of pre-crash pedestrian detection is best addressed by using radar for target ranging and passive infrared for distinguishing of pedestrians from the road environment. Radar sensors being developed for ACC (adaptive cruise control) could be used for the early prediction of a collision, before shorter range radars which cover a much greater angle continue

to track targets in closer proximity to the vehicle. An alternative solution would be to use an active transponder. It is suggested that this would be very inexpensive and would not be severely affected by adverse weather. A summary of sensor types reviewed is given in Table 1.

Table 1.
Summary of sensors used for detecting pedestrians

System	Range	Cost	Carrier freq	Comments
Microwave radar	30-150m	low	60GHz	not affected by darkness
FMCW radar	2-100m	low	76-77GHz	not affected by darkness
Millimetre-Wave real aperture radar	>100m	low	14 or 56GHz	
Active millimetre wave radar	3-100m	low	76-77GHz	
Passive millimetre wave sensors	<150m	low	24GHz 125MHz	insensitive to fog, snow and rain
Infrared sensors	<25m	low	$\lambda=2-4\mu\text{m}$	resolution problems in hot weather
Active infrared (laser/ LED based)	LED 30m (laser 130m)	med/ high	890GHz	will not work in strong sunlight
Lidar	<60m	med	50ns	insensitive to rain, fog, snow but sensitive to dirt
Passive infrared	up to 25m	med	3kHz	more expensive camera required in hot climates
Ultrasonic	8mm - 20m	very low	22kHz 40kHz 50kHz	some clothing does not reflect signal
Active transponder	<20m	low		
Image based (camera)	up to 50m (poor 45-50m)	med	80ms image	strong shadows, poor lighting
Capacitive	up to 2m	low		sensitive to rain and snow

REDUCING PEDESTRIAN INJURIES

As part of the Active Adaptive Secondary Safety (AASS) project, active pedestrian protection systems comprising airbags on the front of a Rover 200 and a Land Rover Discovery were evaluated using computer simulation. A ranking analysis using various factors including the simulation results showed that the pedestrian active protection systems gave high potential for injury reduction (compared with occupant systems which were also assessed by AASS). This was due in part to the ability of the airbag systems to reduce head injuries for an adult, from an unacceptably high level to a relatively low one, which may in practice reduce the injury severity potential for accident victims.

Further work sought to substantiate these claims by testing two full-scale vehicles fitted with a variety of foam padding and airbag devices in impacts with adult and child Occupant Protection Assessment Test (OPAT) dummies at two velocities. The first, 40km/h (25mile/h), was chosen because it is the proposed EC legislative test speed, whilst the second, 48km/h (30mile/h), was chosen because it represented a severe impact to an adult or child and imparts 44% more energy than the first, so is likely to produce much greater injuries.

Pedestrian impact protection systems can be passive or active. The first series of tests were designed to establish the passive performance and show that it was similar to the simulation and close to the EEVC Working Group 17 requirements for the bonnet leading edge and bonnet top. This was achieved through the use of open cell foam padding of a specific thickness to replicate a vehicle structure during impact with an OPAT adult pedestrian dummy. A photograph of the test vehicle is shown in Figure 3.

The same foam padding was then used for the OPAT child dummy impact tests, because a current vehicle would behave in a similar manner irrespective of the size of pedestrian impacted. The only region where this was potentially not true, on the Rover 200, was from the bonnet leading edge to part of the way back towards the windscreen. This could be tuned to be softer for a child head impact on a real vehicle. The EuroNCAP protocol demonstrates this, with several different impact sites chosen for adult and child head forms.

When the foam testing had been completed, another series was designed with airbags inflated by pressurised air gas bottles to provide the requisite airflow and pressure to keep the airbags inflated prior to impact. This was thought necessary because the trajectory resulting from contact would be different from that produced by padding and it was critical to obtain the correct

timing before a pyrotechnic airbag test could be contemplated. This was to emulate an active system with pedestrian sensing capability and to investigate the applicability of air bag technology to pedestrian impact protection.

Impact tests were conducted using airbags positioned on the bonnet leading edge and upper bonnet/windscreen area. Testing was carried out at 25 km/h using an adult OPAT dummy. A photograph of the test vehicle is shown in Figure 4.



Figure 3. Simulated impact protection using foam



Figure 4. AASS inflatable external airbag system

Holding *et al* (2001) reported that for pedestrian impacts at 49km/h (25mile/h), comparing an active adaptive restraint system to the base car performance, the injury reductions recorded for an adult occupant OPAT dummy were:

- HIC₃₆ reduced by 93%
- Chest g reduced by 76%
- Pelvis g reduced by 24%
- Knee lateral angle reduced by 40%
- Lateral knee force reduced by 4%

APVRU - A “PROOF OF CONCEPT” SENSING SYSTEM

The APVRU project concluded that a prototype sensing system should consist of a combination of radar for identification and ranging of targets and passive infra-red for determination of pedestrians from the environment.

Radar sensor

Further to the research in the investigation phases of the APVRU project, the radar unit selected was the High Resolution Radar (HRR) developed by M/A-COM. This unit, designed originally for proximity sensing for the American automotive market, is a short range (0.2-20m), radar operating in the 24GHz ISM Band. The unit consists of a microwave front-end, with an integrated Digital Signal Processor (DSP) and a Controller Area Network (CAN) protocol interface. The horizontal 3dB beamwidth is 55° and the vertical beamwidth is 15°. The publicised range accuracy is $\pm 3\text{cm}$ with an associate resolution of 7cm.

Although capable of Continuous Wave (CW) operation the unit is normally operated in pulse mode and in this mode reports the range and amplitude of the signal reflected back from each of a maximum of ten targets. These are reported, via CAN, using one message for each target on every update cycle (every 20 ms). Targets are assigned identifiers according to their position in a range ordered list, and, if there are less than ten ‘active’ targets (targets that reflect a significant proportion of the transmitted signal), the unit transmits the remaining messages with zero range. The communications load on the CAN bus is therefore constant for each unit.

The radar unit measures 120 mm x 65 mm and is enclosed in a weather proof enclosure with a small push-fit connector, as shown in Figure 5. The ‘printed patch’ transmit and receive antenna are visible of the left and right hand sides of the unit.



Figure 5. M/A-COM High Resolution Radar

Infra-red tracking system

The infrared pedestrian detection and tracking head used for APVRU was an experimental detector platform based around a low element count infrared detector array. This is a novel, low-cost, thermal sensing technology developed by InfraRed Integrated Systems Ltd (IRISYS) with a diverse range of applications in areas such as security, healthcare, retail and transportation.

Infrared radiation is focussed on a 16x16 pyroelectric detector array using a germanium lens giving a 60° field of view, while the array is scanned at just over 30 frames per second. For this application, a long wave pass infrared filter (approximately 6.5 to 15 μm) was employed so that the device was optimised for the detection and discrimination of humans.

The detector platform includes a DSP which enables all low-level signal processing and target tracking to be handled locally. The tracking system is based around an elliptical contour tracker capable of concurrently tracking multiple thermally distinct moving targets with sub-pixel accuracy. This tracking system provides estimates of the position, shape/size, and velocity of multiple, uniquely identified, targets. Since the IRISYS sensor is only sensitive to changes in incident radiation, whilst the tracker only considered smoothly changing elliptical responses, the system was effective at minimising clutter and noise.

In order to develop a combined sensor system with the HRR unit described above, using a common CAN communications interface, a second infrared head was developed for this project. Since the communications bandwidth required to transmit 256 element array data at 30 frames per second was considered to be an unnecessary burden, the head reported only the position within the image plane and unique identifiers of each target. It must be emphasised that, unlike the data returned from the HRR unit, the tracked thermal target identifiers associate the target estimates from one frame to the

next, allowing trajectory information to be accumulated over time. In order to maintain a fixed load on the CAN bus, and in keeping with the radar sensors, blank (null data) messages are transmitted if there are less than ten thermally distinct moving targets in the field of view. The device is housed in a weather proof enclosure as shown in Figure 5 (note: the external cover for the CCD camera was removed when this photograph was taken).



Figure 6 IRISYS Passive IR Head

The prototype sensor array

The final solution used for the APVRU test programme comprised an array of three radar sensors mounted on a roof bar fitted to the test vehicle together with the infra-red array as shown in Figure 7. It should be noted that this arrangement was convenient for development testing and the integration of the sensors within the vehicle was beyond the scope of the project. The three radar sensors were used to provide accurate triangulation of the objects being detected. A schematic block diagram of the system hardware is shown in Figure 8.



Figure 7. Radar and infra-red sensor array fitted to test vehicle

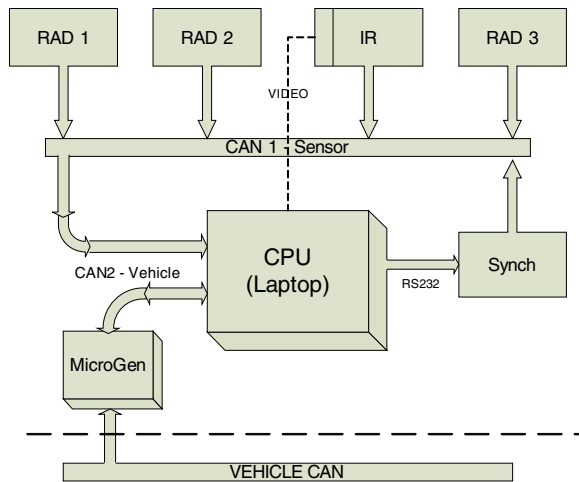


Figure 8. Schematic block diagram of the APVRU hardware system

System software

It is not intended to describe the software used for this work within this paper but a summary of the requirements are listed below:

- Data logging with record and playback functionality.
- Individual radar range filtering (range tracking).
- Computation of ground plane target position measurements from pairs of filtered radar range measurements.
- Combining multiple radar ground plane position measurements with infrared evidence in a multitarget, multisensor, ground plane tracking system.
- Trajectory prediction for determining the likelihood of an impact together with its position and timing.

A schematic block diagram outlining the software is shown in Figure 9. A full description is provided in the APVRU project report (McCarthy *et al*, 2004).

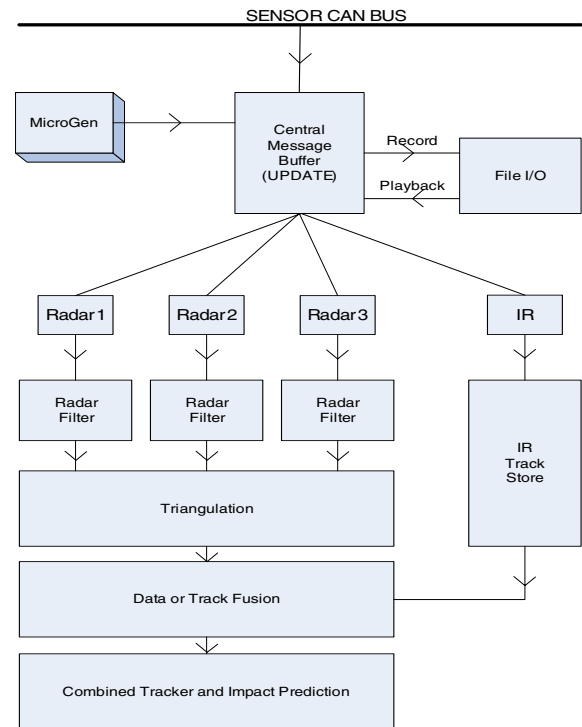


Figure 9. Schematic block diagram showing the system software

APVRU sensor system performance

In order to evaluate the APVRU system, a series of trials of simulated, real-world, accident scenarios, each more progressively challenging were developed. These commenced with a pedestrian walking across in front of the vehicle and then progressed to test angled pedestrian approaches, multiple pedestrians (with different bearings and velocity) and multiple pedestrian movements with roadside clutter in the form of parked and moving vehicles.

As an example of the APVRU system, Figures 10 and 11 show two captured frames from a scenario in which a pedestrian walked along a collision course towards the left hand side of the vehicle. In these frames the right hand side is video (not used by the system) with the IR view plane superimposed. The left hand part of the image shows the ground plane (with 1m grid lines) showing the tracked position of the target (red circle) and the IR azimuth of the target (cyan line). The arrow shows the target's speed and direction, or velocity vector, in relation to the vehicle. The large magenta ellipses are the confidence regions for the triangulated ground plane measurements (one for each filtered radar response). Even though these measurements appear to be poor, the triangulation of the radar combinations is reporting a strong track with an accurate ground plane position, as indicated by the small red elliptical

confidence region around the target's position. The four grey squares at the bottom of the image represent the bonnet of the car. The data in the top left hand corner of the frame shows calculated data from the APVRU system for the time to collision and the probability of impact.

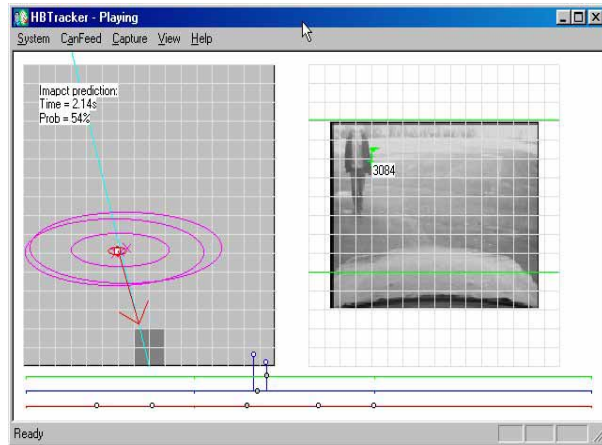


Figure 10. Example of APVRU system tracking a pedestrian

Figure 10 shows that the combined radar and infrared tracking system has successfully locked onto the target and is reporting a high confidence in the ground plane position. The prediction algorithm has estimated a 54% probability of impact. Figure 11 is taken from later in the same sequence, when the pedestrian was 1m from the vehicle. The impact prediction showed a 77% probability with a time to impact of 0.52 seconds. The impact prediction algorithms in this case have indicated that a protective system would be deployed in this situation.

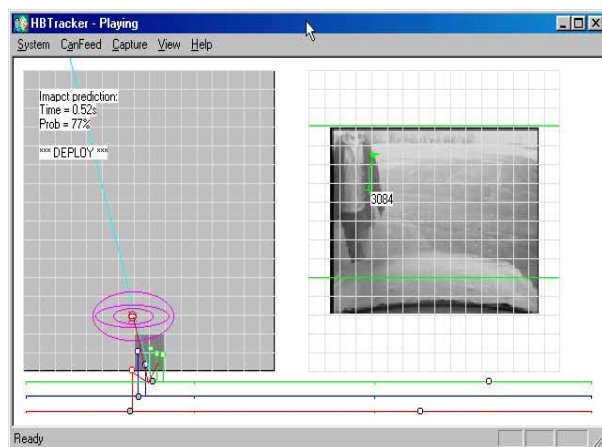


Figure 11. Example of the APVRU system predicting an impact

For scenarios which involved multiple pedestrians the results were more varied. Here the scenarios were more complicated and involved instances where the primary target either hit the vehicle or was a near-miss. For targets with velocity vectors parallel to the vehicle, the system performed well. However, when the primary target had a velocity vector at an oblique angle to the vehicle, while the second target had a parallel velocity vector, there was a tendency to trigger a false deployment for near-miss scenarios. This appeared to be due to excessive velocity smoothing in the tracker together with failures to distinguish multiple targets that merged and then separated, within the time available. However, improvements in raw radar data quality, together with more advanced data association mechanisms within the trackers, would be likely to lead to significant performance improvements.

The APVRU system was tested with a number of simulated real-world, accident scenarios. These are detailed below. Groups 1 to 10 were conducted with human volunteers (approximately equivalent to a 95th percentile male) walking or running at various trajectories toward the vehicle. Groups 11 to 13 were conducted with a moving vehicle and the final group was conducted with the anthropometric dummy with radar and infrared profiles representative of a 50th percentile male developed by the APVRU project.

1. A pedestrian crossing the vehicle left to right or right to left at varying distances.
2. A pedestrian walking along various parallel trajectories toward the vehicle.
3. A pedestrian running along various parallel trajectories.
4. A pedestrian walking along various diagonal trajectories.
5. Two pedestrians walking along various parallel trajectories
6. Two pedestrians walking along various intersecting trajectories toward the vehicle.
7. A pedestrian running past a second pedestrian walking toward the vehicle on parallel trajectories.
8. A pedestrian walking/running at varying speeds across the front of the vehicle and then changing direction toward the vehicle (simulating a pedestrian running into the road).
9. As (8) with a second pedestrian walking parallel toward the vehicle along the pavement.
10. As (8) from behind a parked car.
11. The vehicle driving past a pedestrian standing, at varying distances, at the side of the road.
12. The vehicle driving past two pedestrians walking, at varying distances, at the side of the road.

13. The vehicle driving past pedestrians and vehicles parked at the side of the road.
14. Impact tests with an anthropometric dummy at varying vehicle speeds up to 25kph (15.5mph)

The test speed in the last scenario was due to safety concerns, since both the system operator and driver had to be inside the vehicle during the tests, rather than the performance limits of the system.

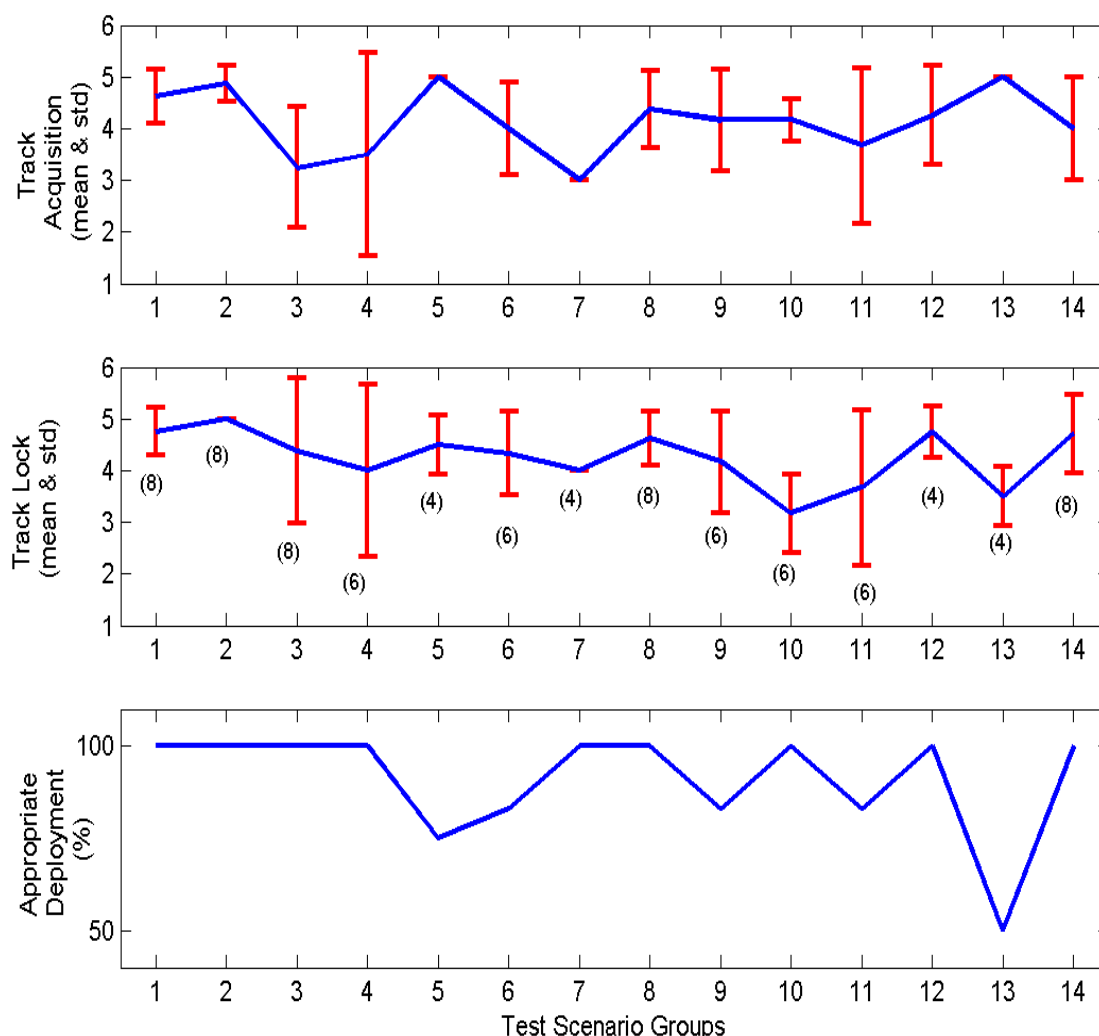


Figure 12. Mean and standard deviation graphs for the system's track acquisition and tracking lock plus the percentage of appropriate deployments

Based on a 5-point scale (1 being "poor" and 5 being "good") the performance of both the system's ability to acquire a valid track and to maintain a tracking lock for each of the test scenarios was graded by subjective analysis. In each case the inspector also graded the appropriate deployment. The mean and standard deviation of each group was calculated together with the percentage of appropriate deployment and is presented in Figure 12. The numbers in brackets on the central graph indicate the total number of individual tests in each grouping.

These results suggest a good to excellent level of performance, apart from the results for group 13 which showed only a 50% appropriate deployment. This data was taken from only 4 tests and was probably due to lower level of prediction accuracy from tracking multiple pedestrians plus parked and oncoming vehicles. In the majority of tests the system accurately tracked the target's position on the ground plane, predicted the probability and/or the point of impact, and would have activated a protective system at what appeared to be the appropriate time, including 25 km/h impacts with a test dummy. However, it should be noted that these were simplified test scenarios in a largely

controlled environment and should only be regarded as evidence of 'proof of concept' for the sensor system.

CONCLUSIONS

The APVRU system has provided the basic foundations of a 'proof of concept' pre-crash vulnerable road user detection system. Such a system may provide the basis of future systems which could decelerate the vehicle to reduce the impact speed and/or deploy an active safety system on the front of the vehicle designed to mitigate the injury to the vulnerable road user.

Data from each of the radars and infrared sensor were successfully synchronised and the data combined in order to track accurately "hot bodied" targets over time. The APVRU system was shown statically to be capable of detecting multiple vulnerable road users in a range of accident scenarios, and was shown, during impact tests, to be capable of detecting a dummy with radar and infrared profiles representative of a human at impact speeds of up to at least 25km/h (15.5mile/h).

However, before such a system is integrated onto a production vehicle, considerable further research and testing is required to ensure system reliability. The APVRU project concluded that it would be beneficial for any final pre-crash system to use radar units integrated with other safety and comfort systems (e.g. Automatic Cruise Control and "stop and go" applications). The vulnerable road user detection radars would need to have a greater maximum and lateral range and an update rate of at least 100Hz (compared with 50Hz for the radars used in the APVRU system).

TRL research has demonstrated the significant injury benefits possible with the use of external airbags to mitigate injury for the primary and secondary impact. However, these test results can only be applied to the specific conditions under which they were tested. Before the possibility of external airbags being fitted to vehicles, the sensor system reliability and airbag deployment must be shown to be effective in responding effectively to the highly complex and variable accident scenarios which are a distinct feature of vulnerable road user accidents. Thus, the first systems employing pre-crash sensor technologies may be linked to driver warning systems and the braking response of the vehicle or an active system which does not confer any increased injury risk other than would occur if the device was not fitted (such as reactive bumper materials or a pop-up bonnet system).

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